鉴别野草和农作物的特异光电子引擎

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摘 要 文章作者在植物光谱识别的基础上提出了一种能够识别不同绿色植物的新颖光电子技术.该项技术运用于可见至近红外波段,在实验室环境和农田环境下,可以成功地采集和分析目标的光谱数据,对不同品种的绿色植物实施了精确识别.该项研究是由跨学科的西澳大利亚微光电子系统中心有限公司(the Western Australian Centre of Excellence for MicroPhotonic Systems, Pty Ltd,)和中国大恒集团公司共同研究完成的,其目标是开发国际上首台野草传感器,使得除草剂的使用定位精确,既可显著提高作物的产量,又可节约80%除草剂,更重要的是保护环境,节约用水,对于农业和生态都有重要意义.

关键词 遥感,精细农业,光子学,系统集成, 电子学

1 引言

至今,田间除草的基本方法还是在耕作周期不同时段定期施洒除草剂.为了保护环境,保护消费者的食品安全,降低农业成本,增加投入产出,有必要对农业中化学制剂的使用加以严格的评估.

近十年来,一些农业创新得到发展,定点施洒除草剂的技术得到应用,从而遏制了在农田中滥用化学药品的现象.先进的电子监测系统和传统的农业机械设备的结合对于实现更多的农业收成来说显然是一条可行的途径,通过精确细致地现场监控田园中的土壤、湿度、营养和其他条件的变化,可以恰当控制种子、化肥和水的用量,这就是“精细农业”的概念.

然而,一旦当传统农机以常规速度行进时,无法精确、实时识别不同的植物,所谓精细农业的目标就难以实现.图1为实时野草监控和除草剂喷洒系统示意图,该系统监测某类野草,一旦探测到该类野草,就将控制信号传给除草剂喷洒系统.

典型绿叶的反射光谱如图1(b)所示,通常在图像中测量植物指数(VI),根据土壤和植物在红光和近红外谱段的差别把植物和土壤区分开(“green from brown”).这里的植物指数(VI)被定义为近红外光(800nm)和红光(650nm)反射率之比[1,2]. 植物的VI指数高于土壤.市场上,主要以VI指数为主的产品有Ntech公司的野草控制系统Weedseeker及Detectspray[3].

尽管实时的对植物和土壤的区分(“green from brown”)探测可能因将除草剂仅仅喷洒在植物上而大量减少除草剂的使用,但仅使用两种波长仍然无法把混杂在农作物中的野草全部鉴别出来.对野草和作物进行航空拍摄和测量的结果进行多光谱分析表明[4],为了鉴别5种已知的野草,如果使用3个不同波段波长的反射光谱进行分析,综合鉴别精度达到56%;使用7个波长达到72%;使用13个波长达到90%;使用22个波长则达到98%.类似地,为了

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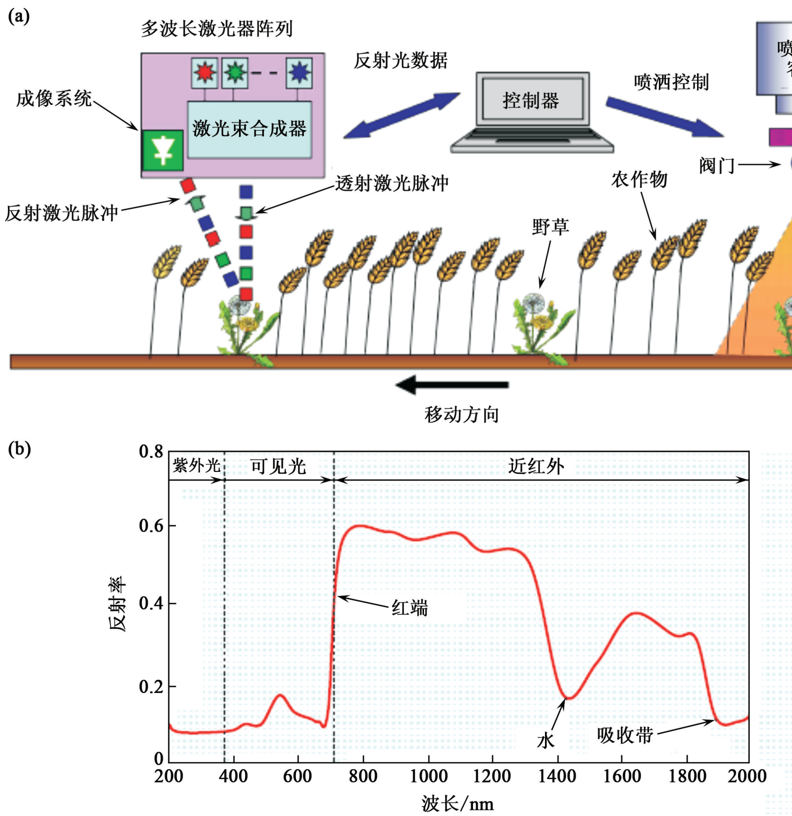

图 1 (a) 野草实时监控和喷洒原理；(b) 典型绿叶反射光谱

鉴别 6 种野草，使用 3，7，13 和 22 种不同波长的鉴别效果分别为 48%，81%，87%和 90%；识别精度的快速提升取决于前 10 到 15 个波段. 上述结果仅依赖于反射光谱. 为了满足鉴别野草的需求，我们在产业界的合作伙伴 Weed Control Australia (WCA)根据上述原理开发了一系列样机，目前它已发展成为该技术的前沿.

该样机的传感组件装在农机喷洒设备上，离地面的高度不到 1m. 该设备仅使用两种波长，根据反射光谱，它能把绿色植物从土壤和植物的断茬中鉴别出来(“green from brown”)，使其针对绿色植物实施喷洒作业，而不是全面积喷洒. 然而如上所述，仅仅使用两种波长，还不能分辨不同的绿色植物. 利用航空和卫星遥感平台进行多波长识别的成本太高，显然并不适用于陆地上的野草识别.

于是，在满足高精度使用要求的前提下，人们开始寻求一种商业上可行的陆基(on-ground)快速识别“引擎”. 陆基识别引擎可以应用人工光源、调制信号、特定波长和叶片尺寸检测等附加技术，是对航摄多光谱分析的延拓.

至今为止的技术只能把绿叶从土壤中识别出来(“green from brown”)，却没有一种商品化技术能将野草从周围的农作物中分辨出来，从而只对野草喷洒除草剂. 一旦上述目标能够实现，相对于非喷洒作物的增产将达到 30%，且对除草剂的节约也将达到 80%. 人们期望因产量提高带来的盈利获益远远超过在除草剂成本上的节约；这两者的结合将会使每公顷毛利率翻倍.

本文介绍一种创新技术，通过将探测光信号波长增至 3 个或更多个，来提高对植物的辨别能力. 我们同时还将根据反射光的响应，证明技术上有可能实现对不同绿色植物的区分(“green from green”).

该项特殊技术还可用于控制道路旁、小径边、铁道、城市和堤岸的野草，以及各种需要对杂草进行选择控制的场合. 利用该项光电野草识别技术，必将提高农业的收成并具有其他效益，调查表明，这项技术在国际市场上具有巨大的潜在需求.

2 光子传感引擎

特殊光子野草传感引擎如图 2(a)所示，它集成了两个光腔，一个 N 波段激光列阵，一个波分复用系统(WDM)，两个准直镜，一个光电探测列阵，一个成像透镜，以及一个控制器(包括驱动电路和信息处理器)，来对不同绿色植物的光谱响应进行鉴别，以实现对不同绿色植物的区分(“green from green”). 只要对硬件略加改造，系统就能容纳十余个不同波长的信号.

系统中的激光被扩束、准直到 4mm 直径，经过波分复用手续，射入光腔. 光腔上下表面分别镀 100% 全反射膜和 90% 分光膜，在每个光腔中输入的准直激光束在腔的上下表面多次反射，每次射到下表面时约有 10% 的能量透过表面照射被测目标区域. 总共有 14 束激光从光腔射出，相邻两束激光的间距为 15mm，空间分辨率比传统的野草探测系统高得多，用此方法可以检测窄叶草.

3—激光束模块如图 2(b) 所示，利用多波段分光膜技术，可使 3 束激光在空间合成一束. 图 3 表示多束激光利用多波段膜在输出表面合成的新颖设计，它构成野草识别系统的基本模块. 激光束照射样品形成的多个光斑的反射光由 1024 个像素的线阵 CCD 记录，每个像素的工作面积为 14μm×14μm. CCD 的分辨率为 12bit，行频高达 68 kHz. 成像传感器前的一个 C 接口的镜头的孔径和焦距可调，将反射像聚焦在像素工作面上.

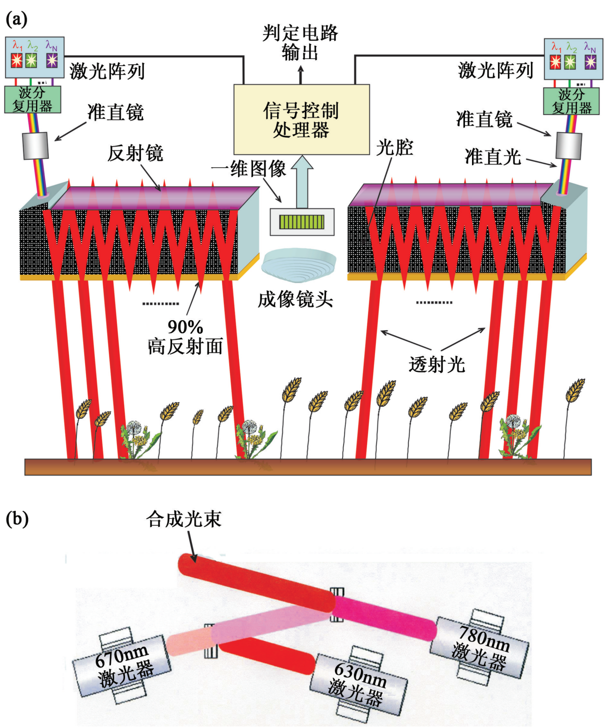

图 2 (a) 野草检测特异光子图; (b) 多波长激光束合成图

图 4 所示为典型反射光光强数据，成像传感器以数字形式记录下的 14 束光斑在背景屏上的投影. 运用平方峰值拟合法，就可确定极大值的强度，然后运用植物鉴别算法. 该算法的计算精度不及高斯拟合，不过后者需要非线性回归运算. 平方峰值拟合的结果如图 4 右上角小图所示.

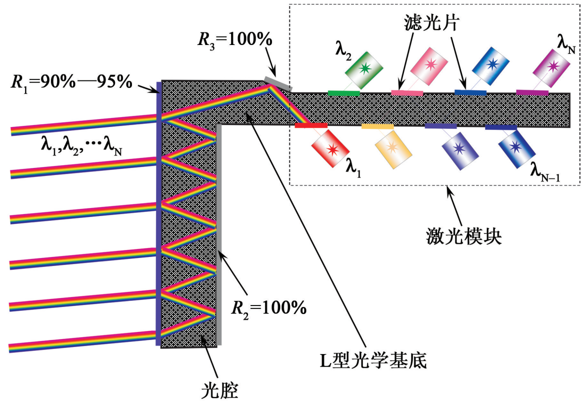

图 3 特异光腔，激光束整合于光腔内

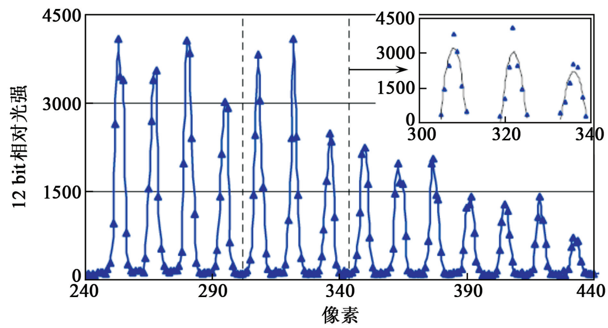

图 4 成像传感器记录的 14 束光斑照在背景屏上的光强轮廓图，右上角小图显示 3 个峰的光强平方峰值

这一特殊技术通过探测植物生物特性的细致变化，对植物进行分类鉴别. 植物的生物特性在一天的不同时刻都在发生变化，并影响反射光的强度值. 数据采集系统使图像采集器与激光排序同步，而激光排序是按照所要求的频率(波长)来进行的，即每个半导体激光器按照给定的频率顺序开关，在对应于某个波长的激光器开启一段时间以后，图像采集器采出一桢图形，包含了被照射植物或土壤的光斑所反射的光强剖面图. 每一光斑对应的峰值强度，用于计算对应的光谱特征，如果该特征和预先记录的野草的特征(又称该野草的光谱“指纹”)相符，就发出“启动”信号给喷洒系统. 图 5 为上述操作的流程图. 上述步骤通过软件触发启动，构成一个采集周期.

图 2(a) 所示的光子野草识别系统具有一些新颖的特征，包括:

(1) 大量的激光成像光斑，导致空间分辨率远高于传统的使用 LED(light emitling diode) 的系统;

(2) 系统对于光学元件的不同轴性要求不高，因为所有波长的信号是重合的，通过光腔中的多光谱全反射，发射光束是彼此平行的;

(3) 利用单个激光器辐射的某一波长的激光产生多个光斑，简化了硬件结构，降低了成本;

(4) 通过直接、简单的方式就可扩展到更多的

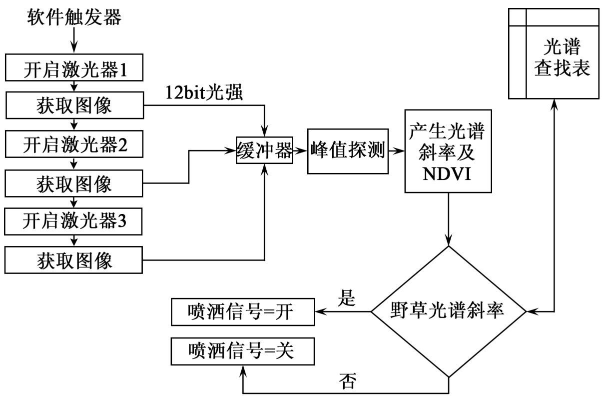

图5 单个采集周期流程图.这一周期要求农机车辆必须行进一段,使投影光斑直径达到4mm,这样做是为了保证采集到的三帧中的每一帧都来自于与植物和土壤对应的空间点

波长(图3).

运用上述光电子野草鉴别系统具有以下许多优点:

(1) 定域喷洒系统的商品化,必然带来显著的经济效益;

(2) 减少除草剂的使用量:由于除草剂根据野草的密度精确地实时、定域喷洒使用,可节约除草剂使用量的80%,因为除草剂仅仅喷洒在野草密度较大处,这将直接节约农民的成本.据估计,仅在澳大利亚,一年的除草剂就花掉10亿澳元.我们估算过,采用本项技术将在很大程度上节约除草剂的费用.

(3) 增加农作物的收成:大面积使用除草剂也将使农作物减产30%,从而精细喷洒除草剂必将改善未使用除草剂地块的农作物产量,据估计,由此产生的收入增长要大于使用农药的支出.此外,根据光谱识别方法,精细使用除草剂的观念也可扩展到精细使用化肥和其他无机物,比如健康的庄稼的光谱特征有别于营养失调的病态庄稼.

(4) 特别有害野草的探测:本技术是一些特别有害的野草的唯一探测方法,例如skeleton weed,由于这种野草,仅西澳大利亚一个州每年就减产5亿澳元.

(5) 除草剂的抗药性的解决方案:与除草剂抗药性的斗争是另一项花费,GRDC估计,根据不同的作物,每公顷大约花费30到100澳元.精细喷洒可周期性地采用不同的(通常是十分昂贵,以公升计)的除草剂,从而有效地减轻了除草剂的抗药性.

(6) 对于州、郡的经济利益:该项技术后对于不同的农作物和不同杂草都有识别的功效,因此还可用于识别及控制路边小径、机场和灌渠边的杂草.

(7) 出口需求:本技术还有很大的潜在出口市场,特别是北美和欧洲.欧洲国家都在积极寻求合理使用除草剂的解决方案,丹麦起到了带头作用.这些国家除草剂的支出约为澳大利亚的20倍.

(8) 农产品出口:某些化学品残留量很低的农产品,即所谓的有机食品,常常会在出口时得到价格补贴.欧盟对于与转基因农作物和食品污染物有关的质量问题也非常敏感.

(9) 节约用水:与目前的设备相比,精细喷洒必将减少水的消耗,并减少喷淋装置的配备使用.根据试验地块的研究,假定野草所占面积为20%,每1000公顷节约用水量高达35,000公升.

(10) 减少污染:减少使用除草剂,必将降低化学品对于土壤、河流和地下水的污染.

(11) 饮用水:除草剂对地下水资源的污染在欧洲和北美是一个越来越严重的问题,特别是当地下水是饮用水源.

(12) 生态平衡:例如,澳大利亚大堡礁的生态环境因除草剂的使用而承受着很大的压力.

(13) 改善土壤品质:由于减少使用除草剂,土壤的品质持续改善.

(14) 有利于健康:由于减少了农作物中除草剂的含量,将必然提高农作物的品质,并有利于民众的健康.

(15) 可持续发展:上述优点是该项技术具有高度可持续发展的特点,有利于持续改善和合理利用自然资源.

3 识别方法

我们利用三种不同波长反射光的强度及其斜率来鉴别野草.斜率S_1和S_2分别定义为

$$S_1=\frac{R_{635}-R_{670}}{\lambda_{635}-\lambda_{670}} \quad , \tag{1}$$

$$S_2=\frac{R_{785}-R_{670}}{\lambda_{785}-\lambda_{670}} \quad , \tag{2}$$

其中λ_n为半导体激光的波长,单位为nm,$R_\lambda=I_\lambda/P_\lambda$为反射率,其中$I_\lambda$为图2所示曲线的峰值强度,$P_\lambda$为光学系统测出的每个光斑的功率,由(2)式定义的归一化差分"植被指数"(NDVI)被用来鉴别土壤和绿叶:

$$\mathrm{NDVI}=\frac{R_{785}-R_{670}}{R_{785}+R_{670}} \quad . \tag{3}$$

对于所有的绿色植物,图1(b)所示曲线的"红端"都非常陡峭(即曲线峰区位于红光波段的斜率非常大),而大NDVI值正是绿色植物区别于土壤和其

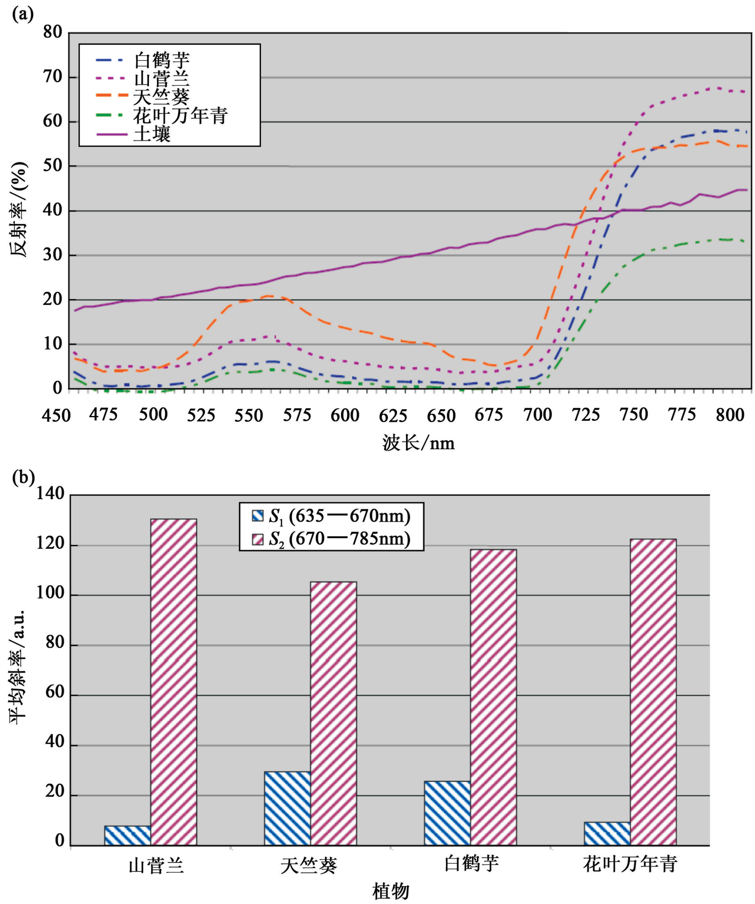

图 6 (a) 四种植物和土壤的光谱反应曲线;(b) 四种植物的平均斜率

他目标的特征.

4 结果和讨论

在实验室中用四种植物的样本来验证原理样机,分别是白鹤芋(Spathiphyllum, 别名苞叶芋),山菅兰(Dianella),天竺葵(Pelargonium)和花叶万年青(Dieffenbachia). 选择这四种植物,是由于它们都适合在室内环境生长. 采用市售的 CCD 光谱仪,可以测得它们的光谱特征,如图 6(a)所示. 特定波长选为 635nm, 670nm 和 785nm,理由如下:在 550—675nm 以及 675—785nm 两个区间内,这些样本的光谱曲线都有较大的斜率;在这些波长范围内都有所要求的半导体激光器件供应.

每种植物的斜率 S_1、S_2 可以由(1—3)式求出,采用任意单位,参阅图 6(b),每种植物至少有一个斜率的值与其他品种不同,因而是可识别的. 所得结果的标准差[5]如图 7 所示. 显然,不同植物的斜率 S_1 和 S_2 不存在同时交叠的情况,表明这些植物是完全可以鉴别的. 测量的总误差来源于成像传感器的暗电流以及激光功率的波动.

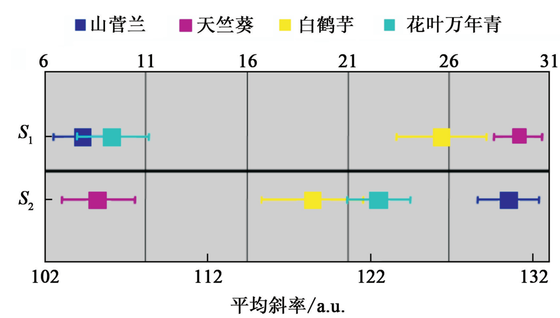

图 7 四种植物的 S_1 和 S_2 斜率平均标准差

为了模拟农业机械的行进,对在转台上安置叶片的样品,以静态和平均 7km/h 到 22km/h 的线速度进行测量,图 8 给出 3cm 宽的白鹤芋(Spathiphyllum)叶片被 4 种激光照射,距离野草传感器的距离分别为 58cm, 69cm 和 80cm 情况下 S_1, S_2 和 NDVI 的所有计算值. 每个数据都是 4 种激光进行 10 次测量的平均值. 测量值的变化主要是由于测量时图像传感器和激光功率的波动引起的.

结果表明,在 7km/h 和 22km/h 的模拟速度下,相对于样品叶片距离的不同,S_1, S_2 和 NDVI 的变化不大. 相对于传感器在一定范围内距离的连续变化是由同一平面内的激光模块和图像传感器模

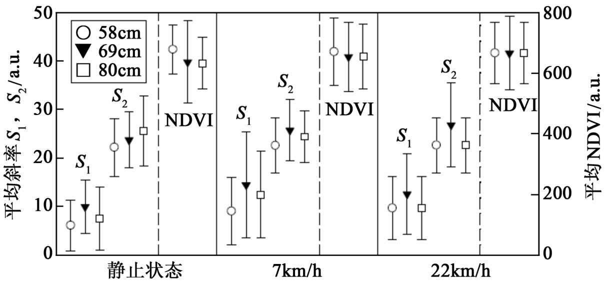

图8　对于白鹤芋(Spathiphyllum)，在静态、每小时7km、每小时22km的线速度下测出的S_1，S_2和NDVI在不同测量距离的平均值. S_1和S_2的值由左边的纵坐标表示，NDVI由右边的纵坐标表示. 圆圈表明测量距离为58cm，黑色三角形表明测量距离为69cm，方块表明测量距离为80cm

块来实现的. 本系统目前的指标为：最小测量叶片的宽度为3cm，行进速度为每小时22km.

如果将控制系统换成嵌入式硬件，叶片宽度可减小为6mm，行进速度则可提升至每小时36km. 前期的静态试验结果表明[6]，野草传感系统能够对有限的绿色植物进行识别. 这些能力使得野草传感系统能够装在农业机械车上对植物进行识别.

如果增加其他波长的激光，则可以改进野草传感器的识别能力. 本装置的空间限制了激光器的数量，但这一点可以由增大图像探测器的帧频来弥补. 将激光器数量增至5个，仍可测量6mm宽度的叶片.

5　未来的进展

本文所描述的光子野草识别引擎已在实验室的环境中演示了植物的识别和野草监控. 为了使该系统最终用于农田现场，目前正在由中国大恒集团公司更新设计，并充分考虑现场环境下的恶劣条件，例如振动、撞击、高温、潮湿和粉尘. 图9给出激光模块和图像探测系统的新设计，在机械设计上考虑了粗调、精调和固紧装置，以便一般农技人员能够使用常规的测试方法装调本系统. 我们对激光束的交叉覆盖、各激光束功率的一致性、激光束和线性图像探测器的调校进行了实验和测试，以保障系统在冲击、机械振动、温度变化的情况下仍能正常工作. 初步结果表明，野草探测引擎能够可靠、稳定地进行植物识别和野草监控. 今后我们将继续报告野草和作物的田间识别结果.

6　结论

我们报告了一种三波长的光子野草识别引擎，

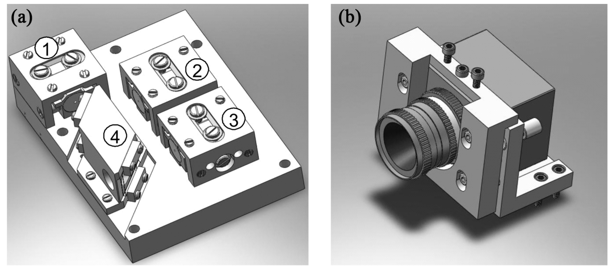

图9　(a)激光模块使用的是①635nm激光器，②670nm激光器，③785nm激光器以及④激光光束耦合调整架；(b)成像传感器选用线阵CCD

发展了一种新的植物识别模型. 由自由空间光腔合成器件以及半导体激光器光学组件辐射的准直激光束阵列，用于照明各种植物，通过测定三个波长的两段光谱曲线的斜率以及NDVI，可将绿色植物从土壤和其他绿色和非绿色目标和野草中鉴别出来. 如果组合更多半导体激光器，增加波长，可以获得关于植物和野草更详细的光学信息.

通过对于行进速度高达每小时22km的农机的模拟实验，证明系统可在以上速度范围内，对不同的测试距离实现对于土壤和绿色植物的识别. 今后进一步的工作是，致力于研发更加稳定、可靠、耐用的结构组件，改进图像传感器件的性能，改善和加强野草识别的精度和性能.

致谢　本研究工作得到澳大利亚研究协会和光子探测系统公司(Australian Research Council and Photonic Detection Systems Pty. Ltd.)的支持，特别要感谢Kaveh Sahba博士在光谱测量方面对我们的帮助.

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附录:《鉴别野草和农作物的特异光电子引擎》原文

Novel photonic sensor engine for discrimination and detection of weeds and crops

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Abstract In this paper, we present a novel photonic sensor engine that enables farmers to differentiate green plants one from another ("green from green") based on spectral plant "fingerprinting". This advanced photonic sensor engine operates in the visible to infra-red wavelength range and enables the capture and analysis of spectral data for accurate discrimination and detection of weeds and crop in laboratory conditions as well as in the field. The sensor is developed through close interdisciplinary research collaboration between the Western Australian Centre of Excellence for MicroPhotonic Systems, Photonics Detection System, Pty Ltd, Australia, and China Daheng Group, China. The outcome of this collaboration is the development of world-first weed sensors that enable site-specific application of herbicides, leading to a significant improvement in crop yield, substantial herbicide savings of up to 80%, environmental benefits, less water usage, and significant improvements to profitability in the agricultural and other sectors.

Keywords remote sensing, precision agriculture, photonics, integrated systems, electronics

1. Introduction

The most widely used practice in weed control is still the spraying of herbicides at different times in the cultivation cycle. Environmental concern for improved consumer safety and more protection of the environment as well as the increase in farm costs and decrease returns for produce have led to a critical evaluation of the use of chemicals in agriculture.

Over the past 10 years, some highly innovative farming practices have emerged, enabling site-specific application of herbicides, hence limiting and controlling the use of agro-chemicals. Technically advanced electronic monitoring systems coupled with traditional farming equipment have made it possible to achieve greater farm profitability by micro-managing the variability of a paddock's soil, moisture and nutrients, which means the delivery of just the right amounts of seed, fertiliser, herbicide or water according to varying soil and other conditions. This farming method is referred to as "precision agriculture".

The ability to accurately identify and/or differentiate plants in real time and at common operating speeds has been a significant missing component of the enabling technologies that make up "precision agriculture". Figure 1 shows the principle of a real-time weed monitoring and spraying system that detects "individual" weeds and passes control signals for spraying only when weeds are detected.

A typical reflectance spectrum of a green leaf is shown in Figure 1(b). The spectral differences between soil and plant at red and NIR wavelengths have been used to detect green plants and to separate plants

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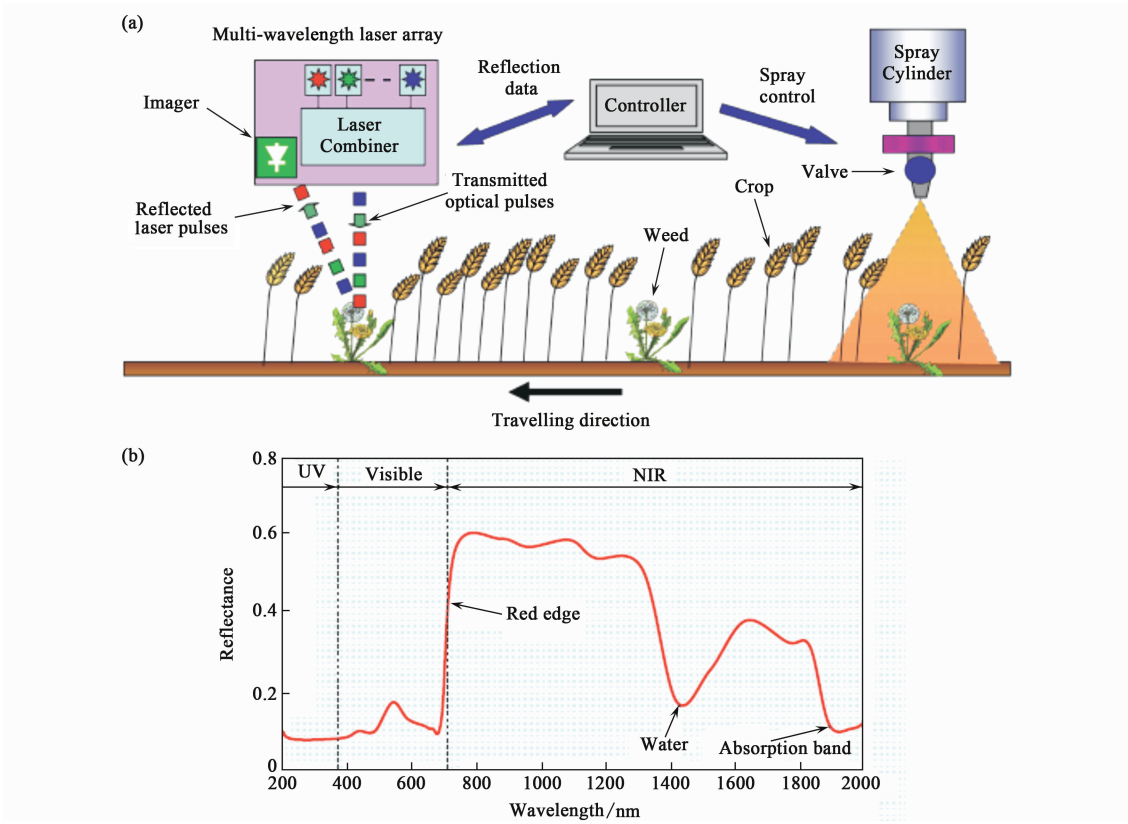

Figure 1. (a) Principle of real time weed monitoring and spraying; (b) typical green leaf reflectance spectrum

from soil ("green from brown") in images by measuring the vegetation index (VI), defined as the ratio of the reflection at NIR wavelengths (800nm) to reflection at red wavelengths (650nm) [1,2]. The VI is high for green plants and low for soil. Commercial, VI-based weed control systems include Weedseeker by Ntech Industries and Detectspray systems [3].

Although on-line "green from brown" detection can lead to a substantial reduction in herbicide use by spraying on vegetation only, the use of only two wavelengths cannot discriminate between green plants with reliability, this being what is required when weeds exist amongst crops. Hyperspectral analysis of weeds and crops has been carried out from an aerial platform [4], and results show that for classifying 5 predetermined weed species, the overall accuracies increased from 56% for 3 bands to 72% for 7 bands, 90% for 13 bands, and 98% for 22 bands. Similarly, for classifying 6 crop species, the overall accuracies increased from 48% for the 3 bands to 81% for 7 bands, 87% for 13 bands, and 90% for 22 bands. The swift increase in accuracy with addition of wavebands is limited to first 10 to 15 wavebands. These results relied on reflected light only. In addressing this need, collaborative industry partner, Weed Control Australia has developed a series of prototypes culminating in the current design.

The current prototype uses sensor modules mounted on agricultural spray equipment less than 1m above ground. It only uses two wavelengths, and has the capacity to differentiate green plants from soil or stubble based on spectral response, allowing precise spraying of green plants only, "green from brown", as opposed to spraying entire areas. However, differentiation between green plants is not possible with only two wavelengths. Whilst plant "fingerprinting" has been achieved from aerial or satellite platforms using multiple wavelengths, these methods are extremely expensive and not applicable for use in a terrestrial sensing application to allow spraying of weeds in real time.

The challenge is to achieve this high level of accuracy with an on-ground sensor engine that is fast and commercially viable. Ground based sensing can augment the techniques used in aerial hyperspectral analysis by using additional techniques such as artificial light, modulated signals, specific wavebands and leaf size.

Although some products can discriminate and spray green plants ("green from brown"), no commercial products are available today to accurately discriminate weeds from surrounding crops and spray just the weeds. Previous research indicates that yield improvements are in some circumstances up to 30% over the non-sprayed crops, in addition to the herbicide savings of up to 80%. The profitability improvements from the higher yield is expected to far exceed the herbicide savings, and the combined effect could double gross profit per hectare.

In this paper, we discuss a novel approach to the improvement of vegetation differentiation through the increase of the number of wavelengths to three or more, and demonstrate that it is technically possible to achieve this differentiation based on different spectral responses. ("green from green")

This core technology can be used to control weeds in other markets such as roadside verges, footpaths, railways, in municipalities and shires and all situations requiring selective weed management. Thus the utilisation of the novel photonic weed sensing architecture will result in significant improvements to profitability in agricultural and other sectors. Market research demonstrates that commercialisation potential exists worldwide.

2. Photonic sensor engine

The novel photonic weed sensing architecture, shown in Figure 2(a), integrates two optical cavities, an N-band laser array, a WDM combiner, two collimators, a photodetector array, an imaging lens, and a controller that includes an electronic driver and a processing unit to differentiate green plants from one another using differences in spectral response ("green from green"). The architecture can scale to tens of wavelengths with a slight modification in hardware.

The laser sources are combined and collimated at around 4mm diameter and the collimated WDM beams are launched into the optical cavity, whose upper and lower sides are coated with a 100% reflection coating and high-reflection coating (around 90%), respectively. Within each optical cavity, the input collimated optical beam undergoes multiple reflections and every time it hits the high-reflection side, a small fraction (around 10%) of its power is transmitted to illuminate a spot in the monitored area. Through multiple reflections with the cavities, 14 spots at a spatial resolution of 15mm are generated, leading to higher spatial resolution in comparison to conventional weed detection systems. This beam resolution allows detection of plants which are narrow leaved, such as skeleton weeds.

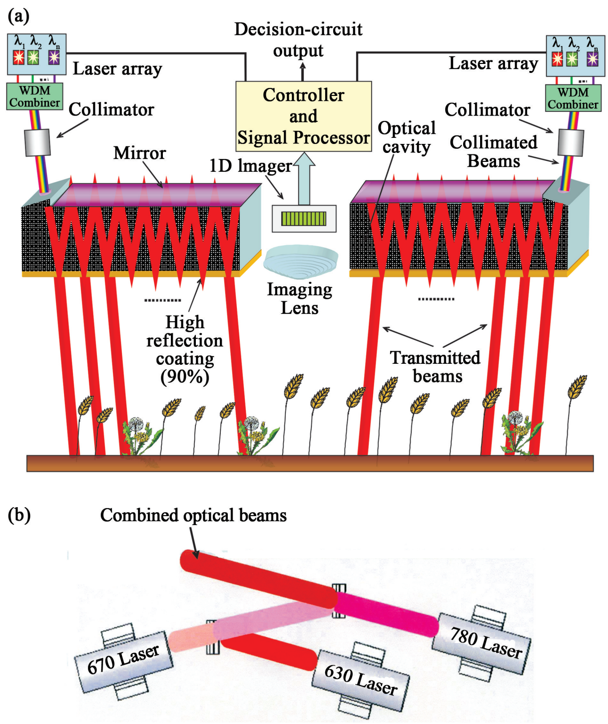

Figure 2. (a) Novel photonic architecture for weed detection; (b) principle of multi-laser wavelength combination

An example of a 3-laser module is shown in Figure 2(b), where multiband thin-film coatings are used to combine the collimated laser beams. Fig. 3 shows a novel cavity utilising multiband thin-film coatings and integrating laser sources of different wavelengths onto its outer surface. This represents a compact solution that enables modularisation of the weed sensor structure. The intensity of the reflected light from the sample illuminated by the multi-spot beam generator is recorded by a line scan 1,024-pixel image sensor, each pixel has an active area of $14\mu m \times 14\mu m$. The image sensor has 12-bit resolution and can operate at a line rate of up to 68 kHz. The image sensor is attached to an appropriate C-mount lens of adjustable aperture and focus that images the reflected light from the illuminated sample on the sensor plane.

Figure 4 shows typical reflected optical intensity

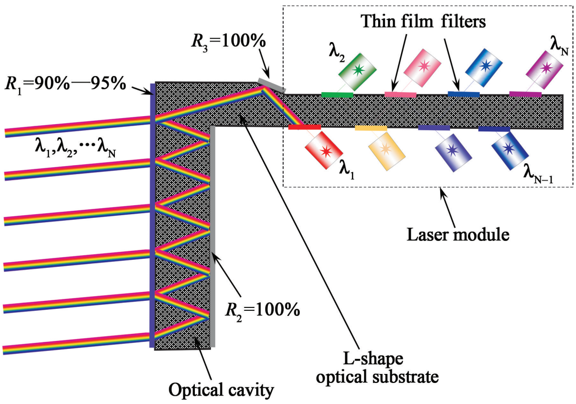

Figure 3. Novel optical cavity, where the lasers are integrated onto the optical cavity

data recorded by the image sensor in digital numbers (DN) for 14 spots projected onto a background screen. As the local maxima of each peak fluctuates, a quadratic peak fitting method is applied to each peak to determine the maximum intensity which is then used in the plant discrimination algorithm. This method is less computationally intensive than Gaussian fitting which requires non-linear regression. The result of quadratic fitting is shown in the inset in Figure 4.

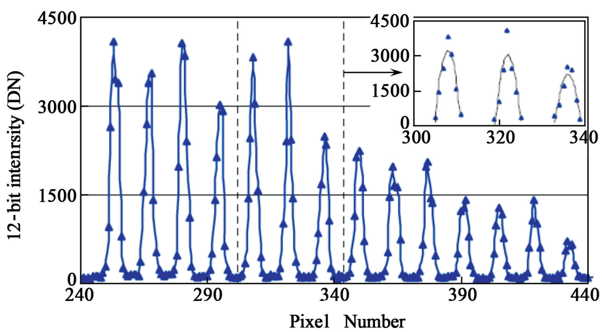

Figure 4. Intensity profile of 14 spots illuminating a background screen recorded by image sensor. Inset shows quadratic fitting of measured intensity profile for three peaks

Novel data processing algorithms have been developed for plant classification and discrimination taking into account the every changing plant phonology which can vary between the hours of a day and affect the reflectance intensity readings. The data acquisition process uses the synchronization of the image frame grabbing and the laser sequencing. The laser sequencing is commenced at a desired frequency (i. e. each diode is turned on and off in sequence at an appropriate frequency). After the desired wavelength from a specific laser has been turned on, the image sensor grabs a single frame containing the intensity profile of the spot array falling on the plant or soil under inspection. The peak intensity value of each spot is extracted and used for calculating the spectral characteristics. If this optical signature matches that of a pre-recorded weed, then an "on" signal is sent to the spraying unit. A logic flow diagram describing this process is shown in Figure 5. These steps form one acquisition cycle and are started at once using a software trigger.

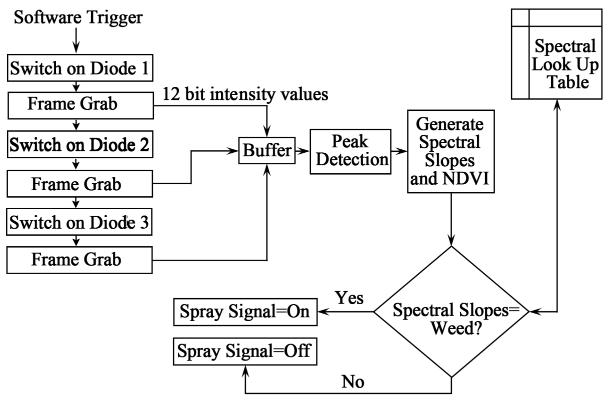

Figure 5. Flow chart for a single acquisition cycle. This cycle must be completed before the farming vehicle has traveled 4mm——the spot diameter of the projected beam. This is to ensure each of the three frames grabbed is from the same spatial points on the plant or soil

The photonic weed sensing architecture shown in Figure 2(a) has a number of novel features, including:

(1) A large number of laser spots are imaged, leading to much enhanced spatial resolution as compared to existing weed sensors which use light emitting diode (LED) illumination.

(2) The system is immune to optical component misalignment, as it keeps all optical wavelengths overlapped and the optical spots parallel to one another through total reflection and multi-band optical coating within the optical cavities.

(3) A single laser source (rather than multiple sources) is used to generate multiple spots for each wavelength, providing a low cost and compressed hardware solution.

(4) It can be scaled to many wavelengths by straightforward modification (Figure 3).

The adoption of the photonic weed sensor will have numerous benefits, including:

(1) Economic benefits expected from successful development of commercial products over and above blanket spraying as per current practices.

(2) Reduction in herbicide usage——Weeds detected can be precision spot sprayed, in real time, saving

in some applications up to 80% of the herbicide applied depending on the weed density——a direct cost saving to the farmer. For example, it is estimated that $1billion is spent per annum on herbicides in Australia alone. Wide scale adoption of the technology would mean significant savings on herbicide expenditure.

(3) Increased crop yield——As some post-emergent herbicides reduce crop yield by as much as 30%, precision weed spraying will result in improved yields on the unsprayed crop. The grower's income in some situations may increase by more than the entire expenditure on pesticides. In addition, precise application of fertilisers through the use of spectral discrimination leads to the improvement in yields by precision management of other inputs, such as fertilisers and minerals. For instance, a healthy plant has a different spectral characteristic from a stressed or malnourished plant of the same species.

(4) Particular noxious weed detection——This technology is the only automatic detection technology available for particular noxious weeds, such as the skeleton weed, which costs western Australian grain growers around $500M per annum.

(5) Solution to herbicide resistance——Combating herbicide resistance is an expensive additional cost (GRDC estimate $30－$100 per hectare depending on the crop) for the farming industry. Precision spraying allows periodic use of a different and usually more expensive herbicide (per litre) to be used sparingly, thus economically killing the herbicide resistant strains.

(6) Economic benefits for municipal and shire councils——The cost savings will apply to many different crop and weed situations in agriculture and also in other areas, such as roadside verges and footpaths for municipal and shire councils, weed control of airports, irrigation channels etc.

(7) Export potential——The technology has potential for export especially to North America and Europe. The EU countries are actively seeking solutions to herbicide usage issues (Denmark has a leading role). The herbicide expenditure in those continents amounts to 20 times that of Australia.

(8) Export of crops——Some agricultural products with low exposure to chemicals are known to attract a price premium (eg. organic food), especially in export markets. The quality of food in relation to GM crops and food contaminants are particularly sensitive issues in the EU.

(9) Water savings——Precision spraying results in reduced water consumption and fewer water refill stops compared to current practices. Studies on the Patchen technology show that up to 35,000 litres of water can be saved per 1000 hectares sprayed based on 20% weed coverage.

(10) Pollution reduction——Reduction of herbicide use will reduce the levels of these chemicals in the soil, rivers and groundwater.

(11) Fresh water——Groundwater herbicide contamination is a growing problem in Europe and North America, especially if the water is used for drinking.

(12) Ecological balance——For example, Australia's Great Barrier Reef is representative of an ecosystem under pressure from herbicide run off.

(13) Improved soil health——by reducing application of herbicides.

(14) Health benefits——Reducing herbicide use on crops will result in improved quality of the crop and to health benefits for the general population.

(15) Sustainability——The above benefits point to the technology's very high "sustainability" credentials and will support the improvement of sustainable natural resource management.

3. Discrimination method

Weed discrimination is based on determining the intensities as well as the slopes in the reflectance at the three wavelengths used. The two slope values, S_1 and S_2, are defined as:

$$S_1 = \frac{R_{635} - R_{670}}{\lambda_{635} - \lambda_{670}} \quad , \tag{1}$$

$$S_2 = \frac{R_{785} - R_{670}}{\lambda_{785} - \lambda_{670}} \quad , \tag{2}$$

where λ_n is the wavelength of the laser diode in nanometers, $R_\lambda = I_\lambda / P_\lambda$ is the calculated reflectance, I_λ is the peak recorded intensity in arbitrary units and P_λ is the measured optical power for each spot generated by the optical structure (Figure 2). The Normalized Difference Vegetation Index (NDVI) defined by Eq. (2) is

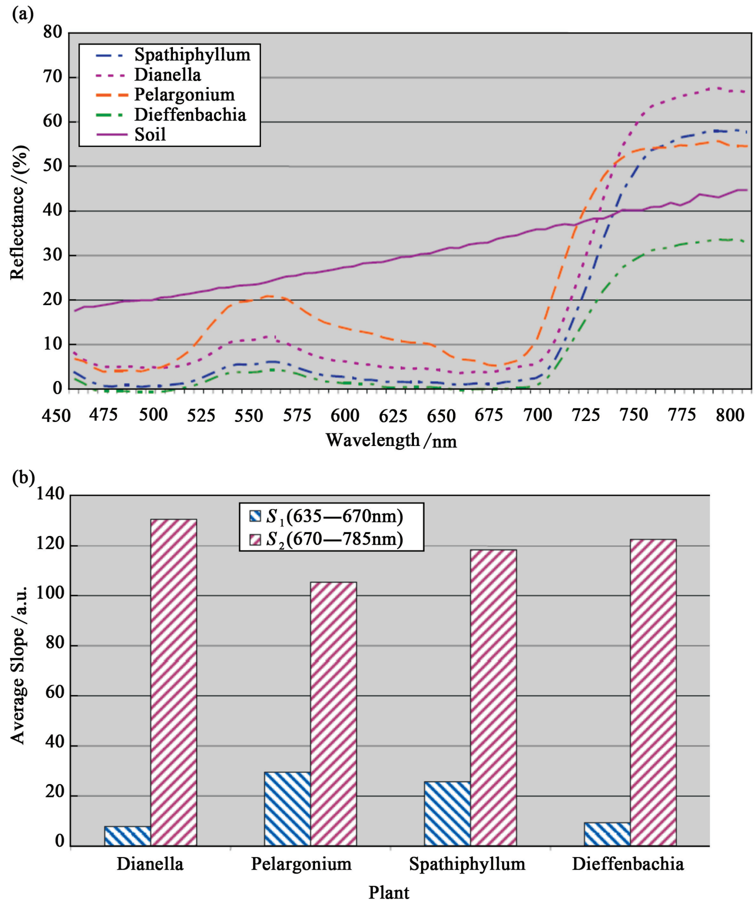

Figure 6. (a) Spectral response of four plants and soil used for experimentation; (b) average slope values for the four sample plants

used to discriminate soils and green leaves:

$$\mathrm{NDVI}=\frac{R_{785}-R_{670}}{R_{785}+R_{670}} \quad . \tag{3}$$

The steep slope of the red edge (Figure 1(b)) results in large values of the NDVI for all green plants in comparison with soil and other objects.

4. Results and discussion

Four sample plants were used to trial the proof-of-concept apparatus in the laboratory. These were spathiphyllum, dianella, pelargonium and dieffenbachia. As house plants, they were selected for their ability to survive in an indoor environment. Each plant was first characterized with a visible, near infrared commercially available CCD spectrometer. The spectral response of each plant's leaf is shown in Figure 6(a). The specific wavelengths of 635nm, 670nm and 785nm were chosen for two reasons. Firstly, the significant spectral slopes between the plants are within the regions from 550—675nm and 675—785nm. Secondly, laser diodes with wavelengths within these regions and the required specifications were commercially available.

The slopes S_1 and S_2 for each plant were determined by using Eqs (1—3). The results in arbitrary units (a. u) are presented in Figure 6(b). Each plant differs in at least one slope value, making it distinguishable. Standard deviations[5] for obtained results are presented in Figure 7. Clearly, no simultaneous overlapping between the slopes S_1 and S_2 of the different plants is exhibited, making the discrimination between the various plants feasible. The total error in measurements is due to the dark current of the image sensor and, predominantly, the optical power fluctuation of laser diodes in time.

The performance of the weed sensor was also tested by simulating vehicle movement with leaf samples mounted on a rotating stage. This test was conducted under static conditions and at average linear velocities of 7 and 22km/h. All calculated values of S_1, S_2 and NDVI, which are shown in Figure 8, are for 3cm wide spathiphyllum leaves covering 4 laser beams at distances of 58cm, 69cm and 80cm from the weed sensor. Each data point is an average over 10 measurements for four laser beams illuminating the leaf. The variability of the measurements was mainly due to fluctuations in the response of the image sensor and optical power of the laser diodes in time.

Results show that there is no significant change in the calculated values of S_1, S_2 and NDVI for variation in the distance to the leaf sample or for simulated speeds of 7km/h and 22km/h. Consistency over a range of distances from the sensor is achieved by coplanar alignment of the laser modules and the image sensor. The current system is capable of conducting measurement for leaf size as small as 3cm at 22km/h.

Replacing the existing control system with embedded hardware would reduce this minimum leaf size to approximately 6mm at vehicle speed of 36km/h. Previous static results[6] showed that the weed sensor is also capable of limited discrimination of green plants. These capabilities make the weed sensor suitable for plant discrimination when mounted on a farming vehicle.

Improving the discrimination capabilities of the weed sensor is possible with the addition of lasers at other wavelengths. Physical space in the laser combination module limits the number of laser diodes which can be added as does the line rate of the camera. Up to five lasers could be used while maintaining a minimum leaf size of 6mm.

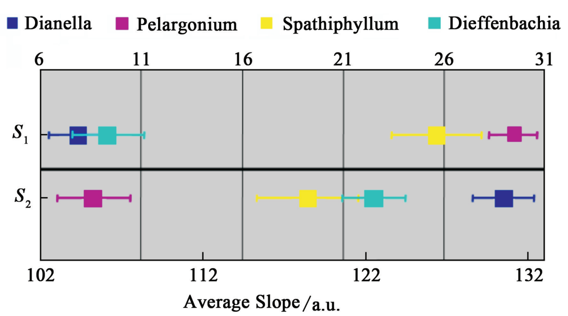

Figure 7. Standard deviation of the mean for slopes S_1 and S_2 for the four sample plants

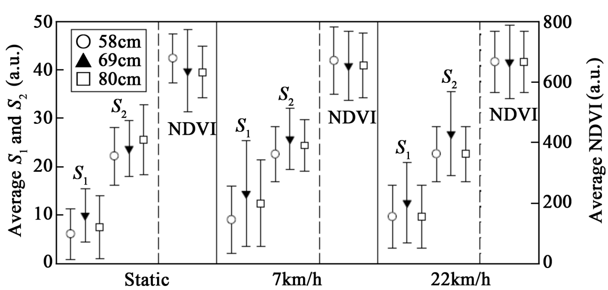

Figure 8. Average values of S_1, S_2 and NDVI for static, 7km/h and 22km/h measurements of spathiphyllum leaf at different distances. S_1 and S_2 are plotted against the left axis and NDVI against the right axis. Circle——58cm, filled triangle——69cm and square——80cm

5. Future work

The above described photonic weed sensor engine has so far been demonstrated for plant discrimination and weed control in the laboratory. To be able to use this system in crop farming fields, a new assembly has been designed and is being developed by China Daheng Group Pty. Ltd, taking into account the harsh environmental conditions such as mechanical vibrations and impacts, high temperature and humidity and dust. Figure 9 shows recently developed and packaged laser module and image sensor. Coarse and fine alignment and locking mechanisms have especially been implemented in order to allow ordinary technicians to align and lock these modules using simple test procedures. Laser beam overlapping, optical power equalisation and laser beam alignment with the linear image sensor are being tested against impact effects, mechanical vibrations, and temperature variations. Preliminary results show that the sensor engine is remarkably robust and reliable for plant discrimination and weed control. Field trial results for weed and crop discrimination will be reported in a forthcoming article.

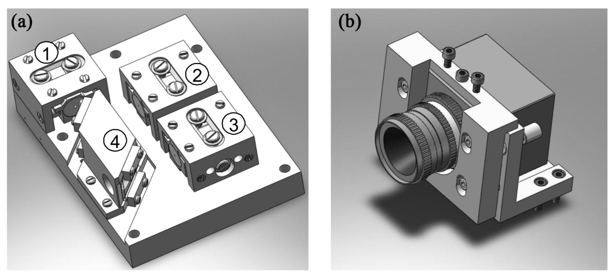

Figure 9. (a) Laser module with ① 635nm, ② 670nm, ③785nm lasers and ④ holder for two laser beam combiners; (b) Image sensor employing a linear optical sensor array

6. Conclusion

A prototype three-waveband photonic weed sensor engine for plant discrimination has been developed and demonstrated. Various types of plants have been illuminated with an array of collimated laser beams emitted through an optical structure integrating laser diodes, free space combiners and optical components. Discrimination of green plants from soil and other green and non-green objects of specific weeds has been achieved by measuring two spectral slopes defined by three wavelengths and NDVI. By designing a laser combination module which accommodates more laser diodes of different wavelengths, a more detailed optical signature can be derived for a plant or a weed.

Operation of the sensor at simulated farming vehicle speeds of up to 22 km/h has shown that it is capable of discrimination between soil and green plants at these speeds over various distances. Future development will focus on the development of robust laser modules and viable packaging to improve the precision of the weed sensor, as well as the implementation of improved image sensors to further enhance the plant discrimination capabilities of the current prototype weed sensor.

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